Electron cooling for the Recycler ring

January 30, 2003

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Background

A charged particle (i.e. an antiproton) traveling in an electron beam undergoes Coulomb scattering with the electrons. The resulting friction and velocity diffusion tends to bring such particles into thermal equilibrium with the electrons. If the particle kinetic energy in the beam frame is high in comparison with the electron temperature, diffusion is insignificant and the particles are cooled – this is, in essence, a simplified description of the electron cooling method. This method was originally suggested by A. M. Budker [1]. It was developed and studied both theoretically and experimentally; an ample list of references can be found in Ref. [2], for example.

Fermilab started in 1995 to investigate the application of electron cooling to 8.9 GeV/c antiprotons in the Recycler as a promising component of an upgrade of Tevatron luminosity beyond the Run IIa goals. The idea was not entirely new at that time; it had been proposed as an upgrade path for the Accumulator as early as 1985 [3], and there had been some experimental work as well as conceptual development [4]. The practice and principles are well established for protons/ions with kinetic energy of less than 500 MeV/nucleon. For ions of higher energy the fundamentals are the same, but hardware development is required and the technical problems differ. Technical details about the Fermilab R&D program can be found in Ref. [5]. To date, electron cooling at relativistic energies remains an unproven technology, and thus constitutes a high-risk segment of the Run2b upgrades plan. Fermilab is currently the only laboratory pursuing the high-energy electron cooling R&D at full scale; conceptual and experimental studies for similar systems are being carried on at Budker INP (Russia), BNL (USA), DESY (Germany), and GSI (Germany).

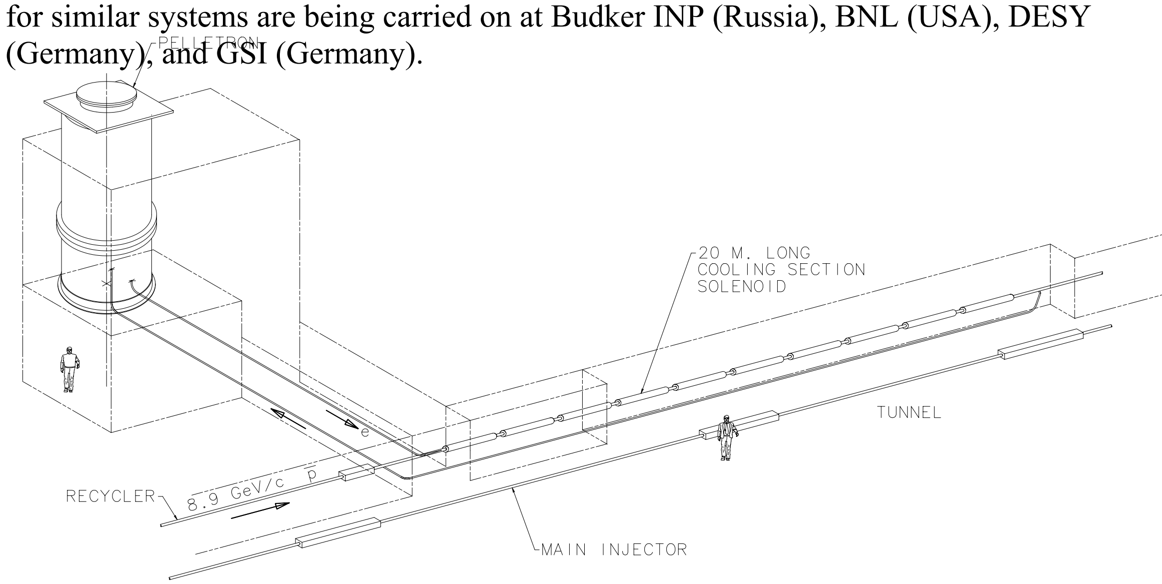

Figure 1: Schematic layout of the Recycler electron cooling system.

The Recycler currently employs a stochastic cooling system to collect multiple batches from the Accumulator. Electron cooling will improve cooling performance in the Recycler, permitting to have faster stacking and larger stacks, and ultimately to re-cool (recycle) antiprotons, which remain at the end of Tevatron stores. In combination with other accelerator upgrades it will permit substantially greater luminosity in the collider. The Recycler electron cooler, discussed here, will be installed in the MI-30 section of the Recycler tunnel and it is schematically shown in Figure 1.

Motivation

Electron cooling can reduce the spread in all three components of beam momentum simultaneously. Its primary advantage over stochastic cooling is that the cooling effect is practically independent of antiproton beam intensity up to the Recycler stack sizes of about 2×10^{13} antiprotons. Its greatest disadvantage is that the effect is very weak until the antiproton emittances are already close to the values wanted in the collider. Thus, the two processes can be seen as complementary rather than competitive. Electron cooling will prove very powerful in the Recycler as an add-on to the stochastic pre-cooling in the Antiproton Source and Recycler.

Purposes of a Recycler beam cooling system (stochastic or electron) are:

1. To re-cool the recycled beam during a time period of the collider store;
2. To aid beam staking in the Recycler during frequent transfers from the Accumulator;
3. To counteract various beam heating mechanisms, such as residual-gas and intra-beam scattering.

For Run2a, the stochastic cooling system alone is thought to be adequate; the attainable emittance cooling rate is thought to be about 15 π mm-mrad/hour (normalized, 95%) for modest stack sizes. Electron cooling and stochastic cooling are complementary, in principle, and, at least, during the earliest operation of the electron cooling system, that complementarity will be exploited by using the stochastic cooling for the large transverse emittance of the recycled antiprotons whereas the electron cooling will be optimized for longitudinal cooling to increase the stacking rate and maximum stack current. At the time of writing this report the Recycler stochastic cooling system has not been fully commissioned.

The ultimate goal is to realize a peak luminosity of 3×10^{32} cm^{-2}s^{-1} in the Tevatron collider by supplying a larger flux of antiprotons. Our conceptual design studies demonstrate that this can be accomplished by providing longitudinal emittance cooling rates in the Recycler of 80 eV·s/h or higher (in conjunction with the transverse stochastic cooling). The specific technical goal for the Recycler with the electron cooling system is to deliver 5×10^{12} antiprotons with a 50 eVs (or less) longitudinal phase-space area (98%) and 10 μm transverse emittance (95%, norm.) in 8 hours.

System parameters

The electron cooling system parameters are primarily determined by the technical goal for longitudinal cooling rates of 80 eV·s/h or higher, and by the electron and antiproton beam matching requirements. At present, all technical parameters for the electron cooling system are optimized for longitudinal cooling only.

The following parameters affect the longitudinal cooling rates:

- It is proportional to the cooling section length. Once the length is set, the optimal value of the antiproton beta-function and the electron beam radius are determined.
- It is proportional to the electron beam current.
- It falls down sharply if the effective electron angular spread in the cooling section is greater than the antiproton rms angular spread $\theta_p \approx 0.1$ mrad. The specific dependence is greatly affected by the nature of this spread: temperature, misalignment, aberration etc.

Figure 2 shows the calculated evolution of a longitudinal antiproton momentum distribution function.

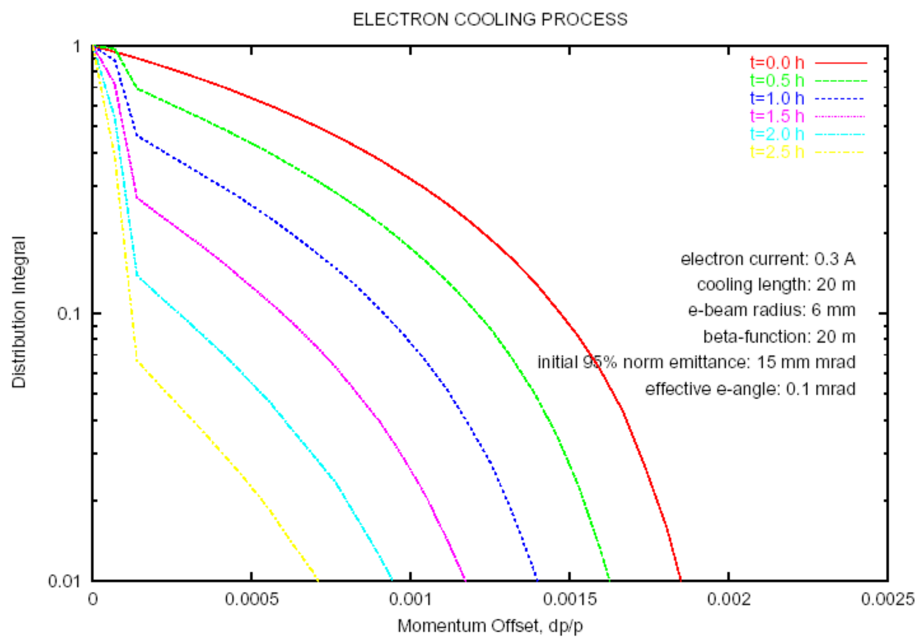

Figure 2: The calculated evolution of the longitudinal momentum spread. The initial distribution is parabolic in momentum; a coasting antiproton beam is assumed to have the total longitudinal emittance of 400 eV-s. The vertical axis represents the fraction of particles outside of the +/- interval for a given momentum on the horizontal axis.

From Fig. 2 one can see that the predicted cooling rates for given system parameters are 22 eV-s/hour. Thus, the required dc electron beam current to meet the 80 eV-s/hour goal is 400 mA or greater.

Table 1 presents important parameters of the Recycler electron cooling system.

Table 1: Electron Cooling System Parameters

Parameter	Value	Units
Electrostatic Accelerator		
Terminal Voltage	4.36	MV
Electron Beam Current	0.5	A
Terminal Voltage Ripple	500	V (FWHM)
Cathode Radius	2.5	mm
Gun Solenoid Field	≤ 600	G
Cooling Section		
Length	20	m
Solenoid Field	≤ 150	G
Vacuum Pressure	0.1	nTorr
Electron Beam Radius	6	mm
Electron Beam Divergence	≤ 80	μrad

These parameters identify a system, which is unlike any other electron cooling system in the world. Several important features, not reflected in Table 1, make this system unique:

- It requires a 4.36 MV power supply operating with a 2-MW beam in a high-efficiency recirculation regime. Our choice of a commercial 4.36-MV Van-de-Graaff type supply forced us to undertake an R&D of three new technologies in **beam transport, beam cooling, and magnet technology**.
- Interrupted solenoidal field: there is a magnetic field at the gun cathode and in the cooling section, but no field in between. The electron beam line is an angular-momentum-dominated transport line – **a new type of beam transport**;
- Low magnetic field in the cooling section: 50-150 G. Unlike low-energy coolers, this will result in non-magnetized cooling – **something that has never been tested**;
- A 20-m long, 100-G solenoid with extremely high field quality – **a solenoid of this type has never been produced**.

Research and development goals

To address the R&D issues and to achieve the required system parameters Fermilab has created an electron cooling R&D facility at the WideBand Lab building. This R&D program was registered as an approved Fermilab experiment E-901. A 5-MV Van de Graaff accelerator (Pelletron) has been purchased and installed at WideBand. This accelerator together with an electron beamline forms an R&D facility. A prototype beamline closely resembles the final beamline. Most of its elements will be reused in the MI/RR tunnel. In addition, all of the Pelletron equipment will be reused. The purpose of this R&D program is to develop a system ready to install in the Recycler tunnel. The program, however, will come short of actual antiproton beam cooling – this will be commissioned in the Recycler ring.

Table 2 presents the electron cooling R&D goals.

Table 2: The electron cooling R&D goals

	Goal	Achieved?
• Recirculated electron beam current	0.5 A	YES
• Electron beam kinetic energy	4.3 MeV	YES
• Beam angular spread (cooling section)	80 μrad	Not yet
• Magnetic field at the cathode	600 G	YES
• Beam diam. at the cathode	5 mm	YES
• Energy spread (FWHM)	500 eV	YES
• Pressure (cooling section)	1×10^{-10} Torr	Not yet
• Recirculation stability (ave.)	1 hour	NO 20 min@3.5 MV <4 min@4.3 MV
• Beam recovery time	5 min	YES (20 sec)
• Typical time between tank openings	1 month (initial) 6 months (final)	YES

It was determined that the most effective way to achieve these goals was to proceed in two stages by: (1) demonstrating the beam current, voltage and necessary stability in a short 10-m long beamline and (2) commissioning the full-scale 60-m long beam line prototype. At present, the R&D program is in its second stage. The status is described below.

Status

The beam recirculation test

- The beam recirculation experiment with a short beam line has been completed. Most of the experimental goals have been attained, the experiment is now entering the next stage: electron beam properties measurements.
- The recirculation system beam line has been disassembled to allow for an installation of a longer full-scale beam line.
- At the kinetic energy of 3.5 MeV and the electron beam current of 0.5 A, the beam can be recirculated with 1 to 3 short interruptions per hour.
- The use of a protection system, allowing to shut the gun off during interruptions, and the so-called crash scraper, intercepting the beam in the transition time, helped to avoid large drops of the Pelletron voltage and large pressure jumps. As a result, the beam recovery time is as low as 15 seconds.
- Better understanding of beam optics and improvements in the gun and collector design made it possible to recirculate a beam of up to 1.7 A at 3.5 MV for several minutes – it is 6 MW of beam power! The beam current was limited by both the cathode emission ability and the maximum gun voltage.
- Acceleration tubes have been replaced in an attempt to avoid HV tube strength deterioration during beam operations. The tube performance without beam did improve, and immediately after initial tube conditioning the Pelletron was stable at 5 MV. At the design voltage of 4.34 MV, the maximum attained beam current was 0.6 A. Nevertheless, reasonable beam stability (~ 10 min between interruptions in long runs) was found only at beam currents below 200 mA.

Higher currents provoked full discharges in the deceleration tube that eventually deteriorated the tube strength. For the final set up in the Recycler tunnel, the Pelletron tank and HV tubes will be extended by an additional 1-MV section. Such an extension at Wideband building is not possible due to limitations in crane and roof heights.

The full-scale beam line

- All elements of a long beam line prototype are currently being installed. A 90-degree achromatic bend has been measured with a proton beam and has shown a good field quality. Operations with a beam in the full-scale beam line will start in the beginning of 2003.

Cooling section solenoid

- The cooling section solenoid consisting of 9 identical 2-m long modules has been installed in a mock-up tunnel. Measurements of a solenoidal magnetic field show that a satisfactory field quality can be reached after a careful adjustment of all correctors. This adjustment will be done after installation of all vacuum elements in the cooling section.

Civil construction

- The architectural design of a new building to house the electron cooling system in the Main Injector/Recycler tunnel has been completed.
- The construction will begin on March 3, 2003 and will last about 300 days.

Project plan

Although electron cooling is well understood, the Recycler application represents a major step in beam energy, to 8 GeV from less about 0.5 GeV. The step is large enough that the high voltage generator, beam transport, and cooling region all require extension of the state of the art. Therefore, about 1 year (as of January, 2003) of research and development activity are likely to precede introduction of any electron cooling equipment into the Recycler.

The R & D phase of the project has the following plan:

1. To develop an optimized system parameter set (finished);

2. To procure and commission a reliable 4.3 MV electrostatic power supply (finished);

3. To design and build an electron beam gun, collector and short (10 m) U-bend transport system to sustain a recirculating current of at least 0.5 A for 1 hour (finished);

4. To design and implement a precise matching from discrete-element beam transport to continuous cooling region solenoid;

5. To design and implement a 20 m cooling section with uniform axial magnetic field with precision such that electron beam transverse angles are $\leq 10^{-4}$;

6. To design and implement magnetic shielding to protect the electron beam against the magnetic fields of the MI/RR tunnel;

7. To design and build beam instrumentation and control to maintain alignment and equal mean velocity of electron and p-bar beams to precision $\leq 10^{-4}$, to measure beam angular spread and position, to determine neutralization, *etc*.;

8. To assemble a full-scale (60 m) beam line, commission it and establish a recirculating beam current of at least 500 mA at 4.3 MeV, sustainable for 24 hours with a duty cycle of no less than 90%;

9. To demonstrate by measurements that the electron beam angles in the cooling section are $\leq 10^{-4}$.

The hardware aspects of the development program are treated in detail in Ref. [5]. The remainder of the work constitutes an Accelerator Improvement Project of moderate scale.

The basic tasks are:

1. Architectural design and civil construction of an enclosure for the high voltage generator and an interconnection tunnel to the MI tunnel for the electron beam transport. The work on this task has already started by Fermilab's FESS;

2. Installation of a Recycler lattice insertion for the cooling region. This task is almost finished. The Recycler lattice suitable for the electron cooling system exists. However, some p-bar trim magnets, diagnostics, and vacuum equipment will have to be installed upstream and downstream of the cooling section at the time of the cooler installation;

3. Installation of cooling section and electron beam transport channels;

4. Commissioning of the cooling system.

References

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